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Characterization of Soft Breakdown Effects for Post-deposition NH_3 Plasma Treated HfO_2 Gate Dielectrics

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1. Introduction

Recently, hafnium dioxide (HfO_2) and its aluminates, silicates and oxynitrides [1-3] have become the most promising candidates for next generation gate dielectric application owing to the sufficient high dielectric constant (15~30), wide energy bandgap (>5 eV), and high thermal stability with the poly-Si gate. Nevertheless, characterizing the reliability of hafnium gate dielectrics is extremely challenging due to the appearance of soft breakdown (SBD), especially for the film thickness scaled below 5 nm. The soft breakdown of HfO_2 films is reported to be area dependence and lower weibull slope of time-to-dielectric-breakdown distribution as compared to the hard breakdown (HBD) [4]. In this work, we for the first time investigate the breakdown modes of HfON gate dielectrics. The dependence of gate area, oxide thickness and stress current density on breakdown modes is entirely studied. Possible leakage paths of soft breakdown are also proposed to clearly understand the breakdown of HfON gate dielectrics.

2. Experimental

Al/TaN/HfO_2/p-Si capacitors with areas of 6.36×10^{-5} and 2.54×10^{-4} cm^2 were fabricated on 4 inch p-type Si wafers. First, the 4 and 12 nm thick HfO_2 films were deposited by a electron beam evaporation. After the gate dielectrics had been formed, the samples are treated by NH_3 plasma at 20W for 5 min. to form the hafnium oxynitride (HfON). A TaN film of 25 nm is then deposited by a sputter. Thereafter, a 500 nm thick Al film was deposited on the TaN film by a thermal coater. The gate of the capacitor was then defined lithographically and etched. Finally, a 500 nm thick Al film was also deposited on the backside of the wafer to form the ohmic contact. The effective oxide thicknesses (EOTs) of 1.23 nm for 4 nm and 4.65 nm for 12 nm thick HfO_2 films were estimated from the strong accumulation region of the high frequency (0.1 MHz) capacitance-voltage (C-V) curves without deducting the quantum confinement effect. The electronic spectrum-scope for the chemical analysis (ESCA) spectra were observed by using a PHI 1600 spectrometer. Moreover, the electrical properties are measured by using an HP4156B semiconductor parameter analyzer and an HP4284A precision LCR meter.

3. Results and Discussion

Fig. 1 shows the Hf 4*f* ESCA spectra of the as-deposited and the post NH_3 plasma treated HfO_2 gate dielectrics. Compared to Hf-O bonds in Hf 4*f* spectra of the as-deposited sample, Hf 4*f* spectra of the post NH_3 plasma treated sample reveals the Hf-N bonding, indicating the nitrogen incorporation to form HfON after our treatment. Fig. 2 shows the breakdown characteristics for the 1.23 nm HfON gate dielectrics under –0.1 A/cm^2 stress. Digital soft breakdown (D-SBD), analog soft breakdown (A-SBD) and hard breakdown are observed. Fig. 3 shows the current density vs. gate voltage (J-V) characteristics of fresh and degraded HfON gate dielectrics with EOT of 4.65 nm under –0.1 A/cm^2 stress. Significant increase of the leakage current is obtained for the analog mode SBD. Fig. 4 shows the generation probability of each mode as a function of stress current density, capacitor area, and oxide thickness. Digital and analog SBD occur mainly in thin and thick gate oxide respectively, and the generation probability of SBD increases with capacitor area. Note that the digital SBD can be observed in thick oxide when gate area and stress current density are sufficiently small. Fig. 5 shows weibull plots of charge-to-breakdown (Q_{bd}) of HfON gate dielectrics with various EOTs and gate areas. Large Q_{bd} is obtained at thin gate oxide and small gate area. Fig. 6 shows the possible leakage paths of soft breakdown for HfON/Hf-silicate stacked structure. Prior breakdown of Hf-silicate owing to the high electric field applied [4-5] is proposed, leading to the apparent soft breakdown effect of the hafnium gate dielectrics.

4. Conclusions

For the first time, the breakdown modes of HfON gate dielectrics using post-deposition NH_3 plasma treatment were investigated. Two types of SBD, digital and analog modes, occur mainly in thin and thick oxide respectively. Moreover, the Q_{bd} increases as oxide thickness and gate area decrease. The apparent SBD of the gate dielectric must be due to the prior breakdown of Hf-silicate that sustained a high electric field. Detailed mechanisms of SBD for HfO_2 gate dielectrics will be proposed in our future study.

References

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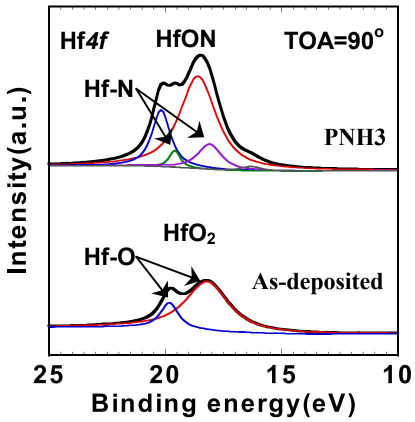

Fig. 1 Spectrum-scope for the chemical analysis (ESCA) spectra of HfO_2 gate dielectrics using post NH_3 plasma treatment. The formation of Hf-N bonding is observed after our treatment.

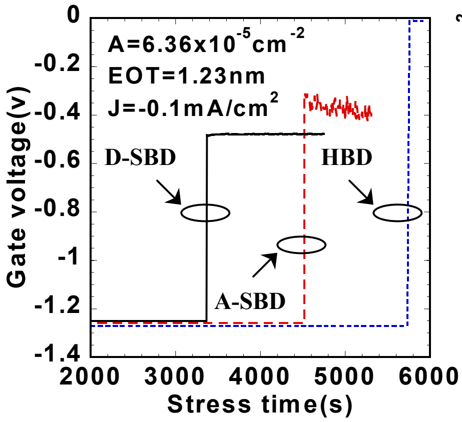

Fig. 2 Charge trapping characteristics of HfON gate dielectrics. Hard breakdown (HBD), analog soft breakdown (A-SBD) and digital soft breakdown (D-SBD) are observed. Constant current stress (–0.1 mA/cm^2) is applied to the gate.

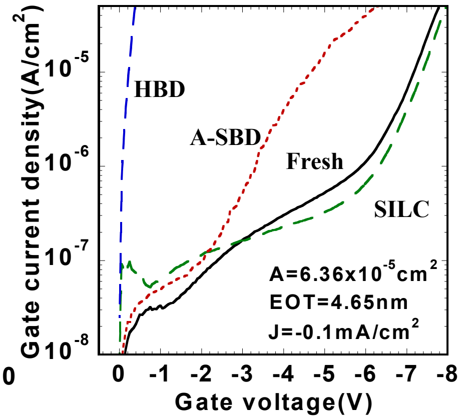

Fig. 3 J-V characteristics of fresh and degraded HfON gate dielectrics with EOT of 4.65nm and gate area of 6.36x10^{-5} cm^2. Constant current stress (–0.1 mA/cm^2) is applied to the gate.

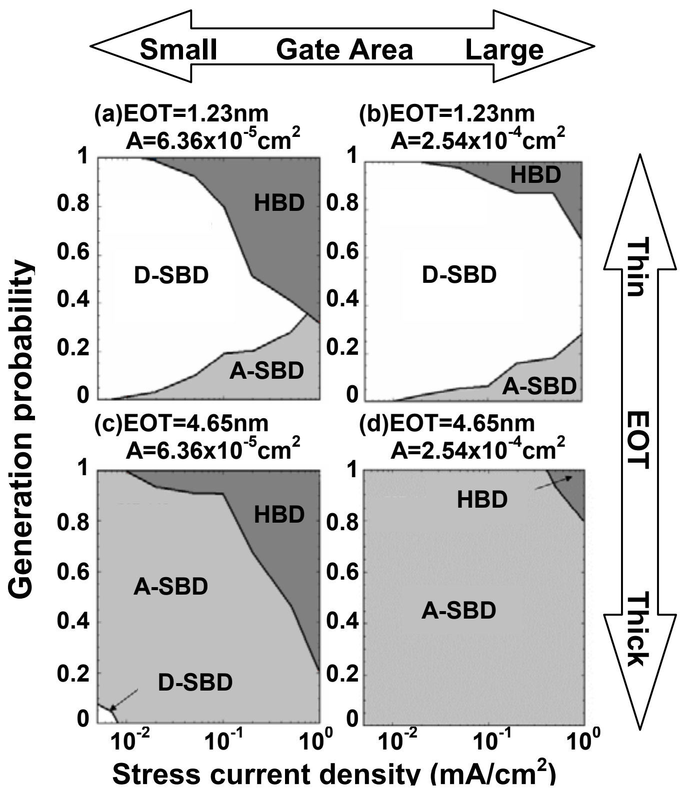

Fig. 4 Generation probability of HfON gate dielectrics for HBD, A-SBD and D-SBD as a function of stress current density, gate area, and oxide thickness.

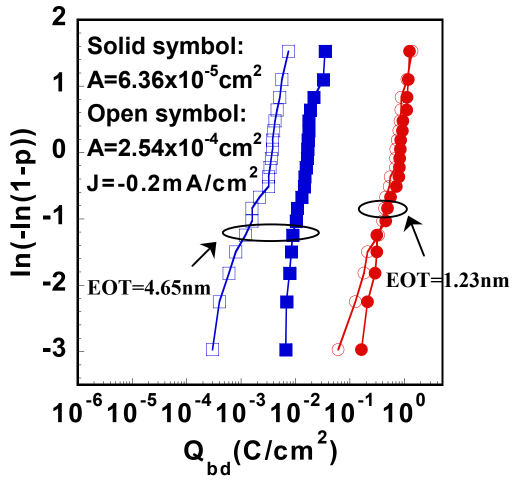

Fig. 5 Weibull plots of charge-to-breakdown (Qbd) for HfON gate dielectrics with EOT of 1.23 and 4.65 nm and gate area of 6.36x10^{-5} and 2.54x10^{-4} cm^2. Constant current stress (–0.2 mA/cm^2) is applied to the gate.

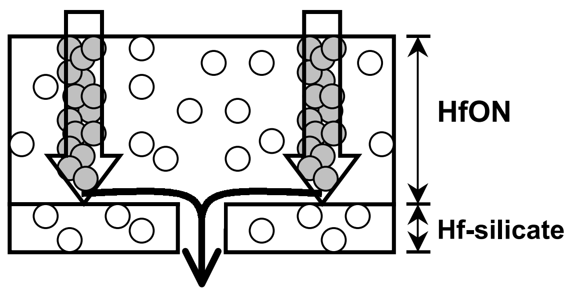

Fig. 6 Schematic view of leakage paths of soft breakdown for HfON/Hf-silicate stacked structure. Prior breakdown of Hf-silicate owing to the high field applied is proposed, leading to the soft breakdown of the hafnium gate dielectrics.